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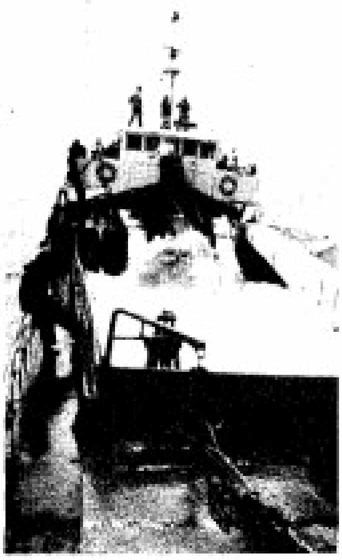

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MISCELLANEOUS PAPER D-87-2

DEVELOPMENT OF A SIMPLIFED COLUMN TEST FOR EVALUATION OF THICKNESS OF CAPPING MATERIAL REQUIRED TO ISOLATE CONTAMINATED DREDGED MATERIAL

by

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A procedure using a small-scale (22.6 ℓ) leaching column was developed for predicting the cap thickness required to chemically seal contaminated dredged sediment from the overlying water column. Several parameters, including dissolved oxygen depletion rates and release rates of ammonium-nitrogen, orthophosphate-phosphorus, and manganese, were evaluated as tracers for use in the predictive test. In addition, several tests were run using potassium chloride amendments to the contaminated sediment prior to capping to determine if this salt would be a suitable tracer. Dissolved oxygen depletion and ammonium-nitrogen release were generally the best tracers to use for predictive purposes. On occasion, orthophosphate-phosphorus release was also an effective tracer. Use of manganese or potassium chloride as tracers proved ineffective.

When large-scale (250 ℓ) verification tests were conducted using various capping

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materials and cap thicknesses that were less than the thickness predicted by the small-scale tests, it was found that these thicknesses were generally unsatisfactory as chemical and biological seals for the contaminated sediments. Tests conducted with cap thicknesses greater than the predicted thicknesses demonstrated that these thicknesses were effective in preventing transfer of contaminants into the overlying water column and the biota in the water column. Sandworms (*Nereis virens*) were able to burrow through the cap material and into the underlying contaminated sediment. As a result, these organisms accumulated contaminants from the underlying sediment.

Overall, the verification tests indicated that the small-scale predictive tests provided the information required to determine the cap thickness necessary to obtain a satisfactory chemical seal; however, it was apparent that additional cap material was necessary to obtain the most effective seal against biological activity. It is important that the cap thickness selected with the small-scale tests be shown to seal a minimum of two of the three parameters used to measure cap effectiveness. To prevent exposure of burrowing benthic organisms to contaminated sediment, it is recommended that a safety margin be added to the thickness required to achieve a chemical seal. This safety margin is determined by the depth to which the deepest burrowing benthic organism within the region can reach. The sum of the thickness required to achieve the safety margin and the thickness required for the chemical seal is the thickness necessary to isolate the contaminated sediment chemically and biologically from the overlying water column and the aquatic biota. This work does not include hydrodynamic effects that may result in resuspension and/or scouring of cap material. Procedures to counter the effects of hydrodynamic processes require engineering considerations that will be addressed in later guidance.

PREFACE

This study was conducted as a part of the Long-Term Effects of Dredging Operations (LEDO) Program, which is sponsored by the Office, Chief of Engineers (OCE). The LEDO Program is assigned to the US Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory's (EL) Environmental Effects of Dredging Programs (EEDP). The OCE Technical Monitors were Drs. Robert Pierce and W. L. Klesch, OCE, and Mr. C. W. Hummer, Water Resources Center, Fort Belvoir, Va.

The study was conducted and the report written by Drs. Douglas Gunnison and James M. Brannon and Messrs. Thomas C. Sturgis and Isaac Smith, Jr., of the Aquatic Processes and Effects Group (APEG), EL. The Analytical Laboratory Group of the EL Environmental Engineering Division conducted sample analyses. Ms. Jamie W. Leach of the WES Information Products Division edited this report. The study was conducted under the general supervision of Dr. Thomas L. Hart, Chief, APEG, Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, and Dr. John Harrison, Chief, EL. Dr. Robert M. Engler was the Program Manager of the EEDP.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

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DEVELOPMENT OF A SIMPLIFIED COLUMN TEST FOR EVALUATION OF THICKNESS OF CAPPING MATERIAL REQUIRED TO ISOLATE CONTAMINATED DREDGED MATERIAL

PART I: INTRODUCTION

Background

Field studies

1. Capping contaminated dredged material in an aquatic environment with uncontaminated dredged material to reduce the ecological impact of the contaminated material and rapidly render it harmless by physical means has been utilized by the New England Division and New York District of the US Army Corps of Engineers in their open-water disposal sites in New York Bight and Long Island Sound. These field studies have shown that capping is technically feasible and that the caps are stable under normal tidal and wave conditions (O'Connor and O'Connor 1983, Science Applications, Inc. (SAI) 1982). However, the efficiency of capping in isolating contaminants in dredged material from overlying water and from pelagic and benthic biota is unknown (O'Connor and O'Connor 1983).

2. A mussel bioaccumulation study at the capping site in the New York Bight indicated low body burdens that could have been due to bioconcentration of contaminants from ambient water as much as from the nearby sediments (O'Connor and O'Connor 1983). Mussels were also suspended in the water column at the sand- and silt-capped sites of the Stanford-Norwalk capping project in Long Island Sound. Concentrations of cobalt, copper, mercury, zinc, and vanadium fluctuated in the mussels over time, but these changes were thought to be unrelated to the presence of the caps because differences in spatial concentrations were not detected (Morton and Kemp 1980). These and other field study results demonstrated that bioaccumulation of contaminants by test organisms in the water column can result from sources other than dredged material. Therefore, determining the ability of caps to isolate contaminated dredged material from the water column has proven to be a difficult question to answer in the field (Morton and Kemp 1980, O'Connor and O'Connor 1983).

Laboratory studies

3. When dredged material testing conducted under Public Law 92-532 (the Ocean Dumping Act) reveals that the potential for ecological harm exists from disposal of dredged material, ocean disposal of that material may be prohibited. Capping contaminated dredged material with clean dredged material following open-water disposal has been accepted by the London Dumping Convention as an alternative to other disposal methods, such as confined land disposal, contingent on the results of ongoing research (Environmental Laboratory 1984). For this option to be accepted on other than an experimental basis, the physical, chemical, and biological impacts and benefits of capping must be better understood. A prime concern is the efficiency of capping in isolating contaminated dredged material from the water column and from the biota, both pelagic and benthic. Several research studies have been conducted to address this concern (Brannon et al. 1985, 1986; Gunnison et al. 1986). However, the procedures used heretofore have been too complex and cost-prohibitive for application to routine use.

4. In the past, the effectiveness of capping in chemically and biologically isolating a contaminated sediment from the overlying water column has been studied using a two-step process (Brannon et al. 1985, 1986; Gunnison et al. 1986) that involves small-scale leaching columns and large-scale reactor units.

5. Small-scale (22.6 ℓ) laboratory leaching columns were used to experimentally assess the cap thickness required to chemically isolate the contaminated dredged material by following changes of dissolved oxygen and selected inorganic chemical species in the overlying water column. The rationale for this approach is as follows. Most contaminated dredged material exerts an oxygen demand on the overlying water column that exceeds oxygen demands normally exerted by uncontaminated sediment. To effectively seal a contaminated dredged material, the cap material must be thick enough to prevent the migration of oxygen-demanding materials into the overlying water column. If these materials are able to diffuse through the cap layer, their presence in the water column will cause a dissolved oxygen depletion rate that exceeds that of the cap material alone. In like manner, once the layer of cap material is thick enough to prevent migration of oxygen-demanding materials into the overlying water column, the oxygen depletion rate observed in the water column will be the same as that of the cap material alone.

6. A similar rationale is applicable to ammonium-nitrogen, orthophosphate-phosphorus, and manganese. These three constituents are released only under anaerobic conditions. Once the anaerobic conditions have been achieved, ammonium-nitrogen, orthophosphate-phosphorus, and manganese are expected to be released. However, if the layer of cap material is thick enough to prevent the diffusing materials from the underlying contaminated dredged material from reaching the water column, the release rates of these materials will be the same as those from the cap material alone.

7. The ability of the predicted thickness of cap material to isolate the contaminated dredged material from both the overlying water column and the aquatic biota was then verified using large-scale (250 ℓ) reactor units. The rationale for these tests is based on the fact that organisms tend to accumulate contaminants to which they are exposed. Thus, if contaminants are moving into the surface layer of the cap material, the biota living on the surface will be exposed to the contaminants and will accumulate them in their tissues. If the contaminants are moving through the cap material and into the water column, then organisms living in the water column will be exposed to the contaminants and are likely to accumulate these materials in their tissues. Analysis of the tissues of these organisms for key contaminants present in the contaminated sediment will then reveal if the contaminants have moved through the cap materials and into the overlying water column and aquatic biota.

8. The major portions of both the cost and the complexity of this two-phase capping evaluation are contributed by the large-scale verification tests. The use of animals in these tests requires a large amount of effort on the part of the several individuals needed to conduct the tests. In addition, the outcome of these tests is made uncertain by virtue of the unpredictable mortality of the animals used in the tests. The large-scale tests also require expensive chemical analyses for contaminants. By contrast, the small-scale tests can be conducted by only one individual, and the chemical parameters monitored are relatively inexpensive.

Purpose and Scope

9. The objective of this study was to develop and evaluate a small-scale predictive test for use in identifying the minimum thickness of a proposed capping material that would inhibit interactions between contaminated

dredged sediment and the overlying water column and aquatic biota. The tests included three highly contaminated sediments and five capping materials. Results of the small-scale predictive tests were verified in large-scale reactor units used to evaluate the effectiveness of the cap thicknesses determined from the results of the small-scale tests.

PART II: METHODS AND MATERIALS

Sample Acquisition

10. Contaminated dredged material and cap material were obtained from various locations around the United States (Table 1). All contaminated sediment samples contained high levels of the constituents indicated in the table. These sampling sites were selected because they contain sediments to be dredged that are considered highly contaminated. Two of the cap materials contained contaminants (Table 1); however, the levels of contaminants in these were not as high as in the contaminated dredged material. In most, but not all, cases the cap materials were selected because they are representative of mateials that are both relatively uncontaminated and likely to be used in a capping operation.

11. Contaminated sediments were removed from navigation channels using clamshell dredges, sampled, and subsequently placed into steel barrels. Most of the capping materials were obtained in the same manner, except for the sand and silt, which were obtained by hand shovel from local Vicksburg deposits. All sediment samples were refrigerated for transport to the US Army Engineer Waterways Experiment Station (WES) and arrived within 5 days after collection. Upon arrival at WES, contents of the barrels of contaminated sediment from a given site were composited, mixed, and then returned to the barrels for storage. Capping materials were also composited, mixed, and returned to their barrels. The sand and silt cap materials were stored in barrels, but in a dry state.

Small-Scale Predictive Tests

12. The ability of the capping material to chemically seal contaminated dredged material containing relatively mobile and oxygen-demanding constituents was determined in 22.6-ℓ cylindrical Plexiglas leaching columns. The design and sediment-loading arrangement of an individual column are shown in Figure 1.

13. Each experiment was conducted in triplicate in a controlled environment chamber with the temperature regulated at $20^{\circ} \pm 0.5^{\circ}$ C. Contaminated sediments were placed into the bottom of the leaching columns to the depth

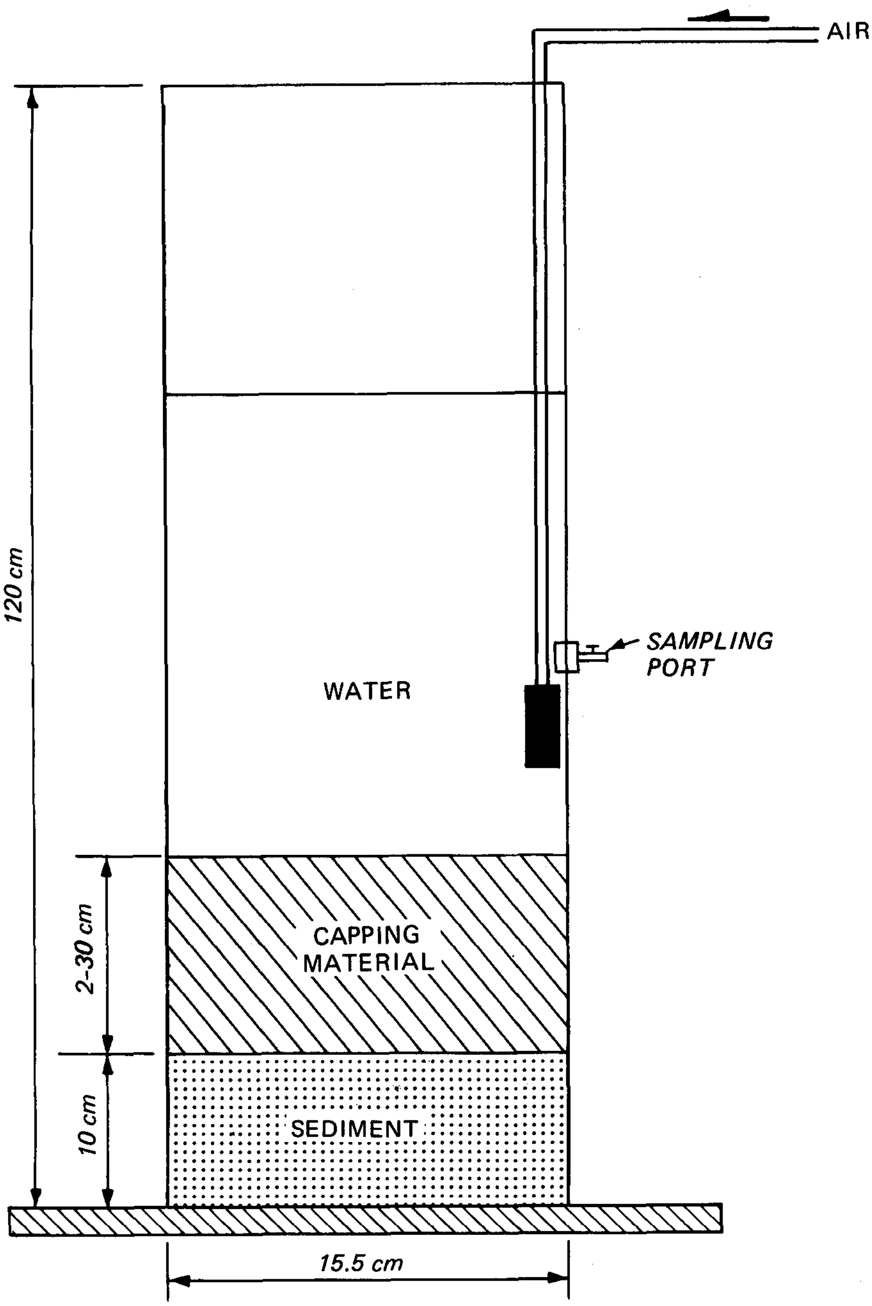

Figure 1. Design and sediment-loading arrangement of small-scale columns used for predictive tests

indicated in Figure 1. Caps of each of the materials tested were placed over the surface of the contaminated sediments in the configurations indicated in Table 2. The depths of the caps ranged from 2 to 30 cm. Uncapped contaminated sediments alone and cap materials alone were each used as controls.

14. Either aged tap water or reverse osmosis water mixed with Instant Ocean™ salts mix to a given salinity was used as indicated in Table 2 to

overlay the test sediments to represent freshwater or saltwater simulations, respectively. Once the leaching column was filled, the water was aerated for 3 days by slowly bubbling air through the water column. This ensured that the dissolved oxygen concentration for all units was at or near the saturation level (within ± 0.5 ml/ℓ) at the start of the experiment. At the end of 3 days, the aeration apparatus was removed, and a 4-cm layer of mineral oil was added to seal the surface of the water column from the atmosphere. The water was manually mixed daily without disturbing the sediment by using a Plexiglas stirring plunger that was suspended between the sediment and the mineral oil layer. Stirring was performed to prevent the establishment of concentration gradients in the water column and to ensure a well-mixed water column. All experiments were conducted in triplicate.

15. Water samples were taken initially and at regular intervals for 30 days or until the measured dissolved oxygen concentration was depleted. Dissolved oxygen was measured in samples collected by permitting water to flow gently from a long tube attached to the reactor unit sampling port into a standard biochemical oxygen demand (BOD) bottle. Dissolved oxygen was determined with the azide modification of the Winkler Method as described in Standard Methods (American Public Health Association (APHA) 1980).

16. Water samples to be analyzed for ammonium-nitrogen, orthophosphate-phosphorus, and reduced manganese (relatively mobile compounds that are released under anaerobic conditions) were cleared of particulate matter by passage through a 0.45-μ membrane filter under a nitrogen atmosphere. Manganese samples were preserved by acidification to pH 1 with concentrated hydrochloric acid (HCl). Manganese concentrations were determined using direct-flame aspiration with a Perkin-Elmer Model 306 Atomic Absorption Spectrophotometer. Samples for ammonium-nitrogen and orthophosphate-phosphorus analyses were preserved by acidification with concentrated HCl to pH 2, followed by immediate freezing and storage at -4° C. Ammonium-nitrogen and orthophosphate-phosphorus were determined using a Technicon Autoanalyzer II in accordance with procedures recommended by Ballinger (1979).

17. To examine further the ability of capping to retard or prevent the movement of contaminants from a dredged material into the water column, an attempt was made to incorporate a tracer compound with contaminated sediment. Contaminated sediments used in this study were from Indiana Harbor and Dutch Kills, while Edgewater and Lake Michigan sediments, respectively, were used as

caps. Potassium chloride (KCl) was added to the Indiana Harbor and Dutch Kills sediments in concentrations of 0.1, 0.5, and 1.0 g KCl/1,000 g (dry weight) of sediment. Both sediments were mixed with the various levels of KCl and placed into the Plexiglas leaching columns in the same manner as for the other capping studies. A 2-cm cap was then added. The Dutch Kills sediment capped with Edgewater sediment was overlaid with 10 ℓ of 20 ppt saline water, while the Indiana Harbor sediment capped with Lake Michigan sediment was overlaid with aged tap water. All columns were allowed to equilibrate for a 3-day period without aeration, and no mineral oil layer was placed on top of the water column. After initial sampling, water samples were taken at 4, 7, 10, 13, 16, 21, 26, 28, 32, 35, 38, and 42 days. No preservation methods were necessary, but sample bottles were sealed to prevent evaporation. At the conclusion of the study, all water samples were analyzed for potassium and chloride using a Technicon Autoanalyzer II in accordance with procedures recommended by Ballinger (1979).

Verification Tests

18. Studies conducted to verify the nature and thickness of cap material required to seal contaminated sediments from the water column and aquatic biota have been described in detail in Brannon et al. (1985, 1986) and Gunnison et al. (1986). This section briefly describes the approach used in the verification procedure. Detailed descriptions of the apparatus, methodologies, and interpretations of the results are presented in the referenced reports.

19. Laboratory studies were conducted to assess the effectiveness of the cap in isolating contaminated sediment. The tests were conducted in a controlled environment chamber at 20° ± 0.5° C, using modified 250-ℓ flow-through reactor units (Figure 2) described in detail by Gunnison et al. (1980). These chambers are 121 cm in height and measure 46 cm on a side. Modifications included sealing of sampling ports with Plexiglas, removal of the mixing pump from the system, and provision for constant aeration of the water column.

20. With the exception of the control, to which only capping material was added, enough contaminated sediment was added to give a layer 15 cm thick on the bottom of each reactor unit. This sediment was then capped with a

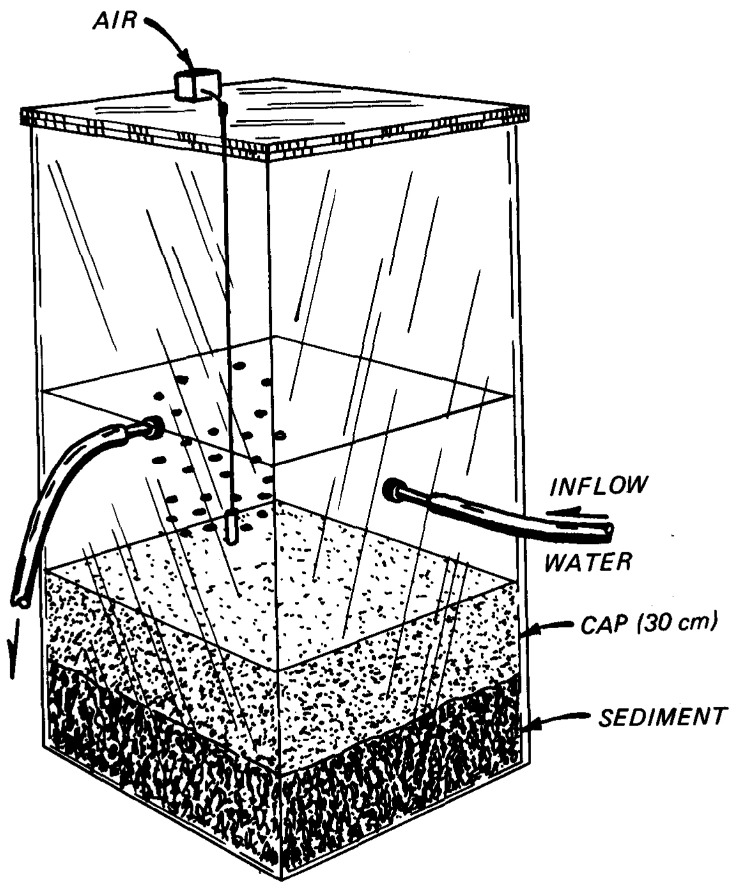

Figure 2. Large-scale reactor units used for verification tests

layer of capping material. The results of the small column predictive studies were used as guidance for the selection of the cap depth used; however, verification work with the Dutch Kills and Black Rock contaminated sediments was done with cap thicknesses that bracketed the predicted thickness, rather than with the predicted thickness. Verification work with Indiana Harbor sediment was conducted using the cap thickness predicted by the small column tests. Additional large-scale reactor units were set up with 15 cm of the contaminated sediment without cap material. Three replicates were set up for each of the three treatments: controls, capped contaminated sediment, and uncapped contaminated sediment.

21. Sixty litres of either aged tap water for freshwater simulations, or water of an appropriate salinity for marine and estuarine tests, were then added as gently as possible to each reactor unit and allowed to equilibrate with aeration for 14 days. A 14-day equilibration time was selected to allow initial compaction to occur and for material suspended during water addition

to settle. At the end of the equilibration/consolidation period, flow-through of aged tap water or saltwater, as appropriate, was initiated at a rate of 1.46 ℓ/hr. At this flow rate, 50 percent of the overlying water column was replaced every 36 hr (Sprague 1969). The water column in each reactor unit was continuously aerated to ensure a well-mixed aerobic water column.

22. The movement of contaminants out of the sediment and into the water column and aquatic biota was monitored by two methods. First, samples of the water column were taken after 40 days of incubation to determine if any contaminants were detectable. Second, aquatic organisms were placed in the large reactor units, both on the sediment surface and in the water column. These organisms were used in a bioassay to determine if contaminants had moved through the cap material and into the water column.

23. Clams were suspended in the water column because of the ability of these organisms to continuously process water through their systems while removing contaminants dissolved in the water or associated with any particulate matter suspended in the water column. The number of clams used was sufficient to permit samples to be removed at both 10 and 40 days of incubation. In the case of the Indiana Harbor sediment, the yellow perch, *Perca flavescens*, was also placed in the water column to monitor exposure to contaminants by an organism native to the Great Lakes area. Organisms placed on the sediment surface were selected for their ability to interact with surface sediments. This was done to ensure contact of the animals with any contaminants that had migrated to the sediment surface and to provide a source of bioturbation for the sediment surface, thus giving a potential source of contaminants in dissolved and suspended particulate form for the water column. For estuarine situations, the benthic organism selected was the sandworm, *Nereis virens*, while the red swamp crayfish, *Procambaris clarkii*, was used for freshwater sediments.

24. Samples of all animals to be used were taken as the animals were placed into the large reaction columns to provide baseline data on the initial contents of any contaminants that may have been present in the animals. Animals were placed into each of the treatments; thus, the accumulation of contaminants was assessed from capped contaminated sediments, uncapped contaminated sediments, and cap materials alone, the latter serving as controls for each of the tests.

Analysis of Results

25. For small-scale predictive tests, means and standard errors were determined for each parameter within a treatment. To obtain oxygen depletion and nutrient release rates, linear regressions were run on each of the means for a given parameter against cap depth. For each regression computed, a correlation coefficient (r-value) was obtained, describing the goodness-of-fit of the regression at the 0.05 level of significance.

26. For large-scale verification tests, means and standard errors were determined for each parameter within a treatment. To determine the statistical significance of differences between means, t-tests were conducted. Statements of significance made were based on the 5-percent ($p < 0.05$) level or less.

PART III: TEST RESULTS

Small-Scale Predictive Tests

Water column oxygen depletion

27. Small column experiments were conducted to determine the thickness of cap necessary to chemically isolate a contaminated sediment from the water column. Dissolved oxygen depletion in the water column would not normally be expected to be a problem in the open-water disposal environment because of mixing and reaeration. Dissolved oxygen depletion, however, can be used as a tracer for determining how effectively a cap can isolate an underlying contaminated dredged material having an oxygen demand that is higher than the proposed capping material.

28. A comparison of the effect of cap thickness on dissolved oxygen depletion rates in the water columns for each of the sediments examined is presented in Table 3. Oxygen depletion rates were determined by performing linear regression analyses of mass uptake or release per unit area (milligrams per square metre) versus time. Rates plotted were the means of three replicates and represent values greater than baseline (i.e., oxygen demand of cap alone).

29. As can be seen in Table 3, there was an initial rapid drop in oxygen depletion rate from that of the uncapped contaminated sediment with the addition of the first few centimetres of cap material for Dutch Kills sediment and for the sand, New Haven sediment, and silt cap treatments of Black Rock Harbor sediment. In the latter case, no statistically significant changes in the dissolved oxygen depletion rate were observed. For the 2-cm cap of Buttermilk Channel sediment over the Dutch Kills sediment, the initial decline in oxygen depletion rate amounted to 42 percent of the depletion rate exerted by uncapped Dutch Kills sediment. For undiluted Black Rock Harbor sediment capped with 2 cm of sand, the decline was 40 percent, while the decrease for the 2-cm silt cap was 81 percent. A 2-cm cap of New Haven sediment over Black Rock Harbor sediment resulted in complete inhibition of oxygen demand above that of the New Haven cap material itself (i.e., oxygen demand attributable to Black Rock sediment was masked by the high oxygen demand from the New Haven cap).

30. No rapid decline was observed for diluted Black Rock Harbor

sediment capped with sand or for Indiana Harbor sediment capped with Lake Michigan sediment. In the oxygen demand rate curve for diluted Black Rock sediment capped with sand, there was little reduction in oxygen demand, even with a 14-cm sand cap. Diluted Black Rock sediment was produced by adding deoxygenated water to Black Rock sediment until the solids content had been reduced to 30 percent from the original 54 percent. This is important because the diluted sediment is more representative of hydraulically dredged sediment than clamshell dredged sediment. The diluted sediment was observed to undergo very irregular compaction when cap materials were added to the surface. In like manner, the Indiana Harbor sediment, which was dredged by clamshell, was between 30- and 50-percent solids and showed no significant decrease in oxygen depletion rate with increasing cap depth (Table 3). The Lake Michigan cap material was also coarse grained (a sandy, gravelly material) and caused very irregular compaction. In addition, placement of extra amounts of cap material was necessary to achieve the specified 30-cm cap over the Indiana Harbor sediment.

31. The cap thickness required to isolate the overlying water column from oxygen demand due to Dutch Kills sediment was 22 cm. Cap depth required to achieve the same for Black Rock sediment was 2 cm for New Haven material, 18 cm for silt, and 22 cm for sand. Sand caps of up to 30 cm in thickness did not totally isolate oxygen demand attributable to the diluted Black Rock sediment from the water column, as was also the case for a Lake Michigan cap over Indiana Harbor sediment.

Nutrient and metal release rates

32. Ammonium-nitrogen. Ammonium-nitrogen release rates to the overlying water, derived in the same manner as oxygen depletion rates, are presented as a function of the thickness of cap material in Table 4. A 2-cm cap of Buttermilk Channel sediment gave an 18-percent decrease in ammonium-nitrogen release rate for Dutch Kills sediment, while a 22-cm cap gave a decrease to the level of Buttermilk Channel sediment alone. Results showed that a 2-cm thickness of all cap materials substantially reduced (42 to 61 percent) releases of ammonium-nitrogen to the overlying water by Black Rock Harbor sediment. There was no significant ($p < 0.05$) release greater than that of the cap material alone when a cap thickness of 22 cm of sand, 18 cm of Vicksburg silt, and 10 cm of New Haven sediment was reached. Capping of diluted Black Rock sediment with sand required a cap thickness of 30 cm to obtain a 63-percent

reduction in release rate. Capping of Indiana Harbor sediment with 30 cm of Lake Michigan sediment gave a 100-percent reduction in the ammonium-nitrogen release rate.

33. Orthophosphate-phosphorus. Generally, use of orthophosphate-phosphorus release as a tracer proved unsuccessful because releases from cap materials exceeded or closely approximated those measured in Dutch Kills and Black Rock Harbor sediments. Use of orthophosphate-phosphorus as a tracer for these sediments was therefore not pursued. For Indiana Harbor sediment capped with Lake Michigan sediment, orthophosphate-phosphorus proved to be a useful tracer, and the results are shown in the following tabulation:

Cap Thickness cm	Release Rate $mg/m^2/day$ (Std Error of Mean)
0	24 (2)
5	18 (1)
15	13 (4)
25	9 (2)
30	5 (2)

A 30-cm cap of Lake Michigan sediment gave a 69-percent decrease in orthophosphate-phosphorus release from Indiana Harbor sediment. Based on these data, a cap thickness of 40 to 43 cm would give a 100-percent decrease in the orthophosphate-phosphorus release rate.

34. Manganese. Determination of cap thicknesses necessary to chemically seal a dredged sediment was also attempted using manganese as a tracer. This tracer proved unsuitable because either the releases from cap materials exceeded or closely approximated those of the cap materials or releases did not occur with the contaminated sediment alone.

Tracer studies with KCl

35. The use of KCl mixed with contaminated sediment to detect potential movement of dissolved materials through the cap and into the water column proved to be totally unsatisfactory. Each of the levels of KCl tested demonstrated some movement of the KCl through a 2-cm cap. In addition, there was a lack of substantial differences in the final water column concentrations of KCl for the various levels used.

Summary of results

36. The results demonstrated that both the thickness and the texture of the sediment cap exerted influence on sediment-water interactions, with cap thickness having the dominant effect. In the absence of cap disruption and with a fairly dense (percent solids above 40 percent) underlying contaminated sediment, a cap thickness of from 2 to 22 cm appeared to be adequate to seal the contaminated sediments from the overlying water column. The effectiveness of the cap materials was in the order New Haven sediment > clay > sand. The effectiveness of the parameters tested as tracers of cap effectiveness was in the order ammonium-nitrogen > dissolved oxygen >> orthophosphate-phosphorus. The latter substance was generally a poor tracer. Manganese was totally unsuitable as a tracer, as were the potassium chloride amendments to the contaminated sediments.

Verification of Cap Effectiveness

37. Generalized summaries of the results of the verification tests are presented in Tables 5-7. Initially, verification tests were carried out to determine the effects of cap thicknesses on the efficiency of capping in preventing impacts to aquatic biota as well as the overlying water column; substantiation of the cap thickness required to obtain chemical sealing of the sediment from the overlying water column as determined by the small-scale predictive tests was a secondary consideration.

Dutch Kills sediment

38. Table 5 presents the results of large-scale verification tests run on Dutch Kills sediment capped with Buttermilk Channel sediment. The required thickness for a Buttermilk Channel cap predicted by the small-scale tests was 22 cm, while actual cap thicknesses tested in the large reactor units were 0, 10, and 50 cm. (It is important to point out that the 22-cm predicted thickness was determined for a chemical seal only and did not include any allowance for bioturbation.)

39. The clam and the sandworm both accumulated contaminants from the Dutch Kills sediment in the uncapped and the 10-cm capped test, but not from the cap material alone (control) or the 50-cm capped tests. Thus, the minimum cap thickness required to obtain a complete seal of the contaminated sediment from the overlying water column and the aquatic biota probably lies between

the 22-cm thickness predicted as being effective from a purely chemical viewpoint and the 50-cm thickness substantiated as being totally effective from both chemical and biological viewpoints.

40. It is important to point out that the sandworm is an extremely effective bioturbation agent, and many of the individuals present burrowed through the entire 50-cm cap and then through the underlying Dutch Kills sediment to the bottom of the reactor units. The clams, which were suspended in the water column, accumulated contaminants brought into the water column by the activities of the sandworm in the uncapped and 10-cm capped treatments, but not in the 50-cm treatment.

Black Rock Harbor sediment

41. Table 6 presents the results of a more comprehensive study in which three different capping materials of widely divergent textural properties were examined for their effectiveness as caps for Black Rock Harbor sediment at two different cap thicknesses. These results are contrasted to those obtained with uncapped Black Rock Harbor sediment. The sandworm was used as a representative of benthic fauna capable of disturbing sediment, while the clam *Rangia* was suspended in the water column.

42. The sandworms again burrowed to the bottom of the reaction chambers, but in this case, the worms each took up some of the contaminants as a consequence of their exposure to the contaminated sediment. The clams in each of the 5-cm capped treatments accumulated contaminants; those in the silt and the New Haven sediment treatments accumulated lower levels of contaminants than did their counterparts in the 5-cm sand treatment.

43. As indicated in paragraph 36, the small-scale predictive tests also showed an influence of texture upon cap effectiveness, with the required thickness to obtain a chemical seal being 22 cm for sand, 18 cm for silt, and 10 cm for the New Haven sediment. A 50-cm cap of each of the cap materials tested was totally effective in preventing the clams from accumulating contaminants. The sandworms, however, managed to accumulate some contaminants in the 50-cm capped treatments, although the levels of accumulation were lower than in the uncapped or 5-cm capped treatments.

Indiana Harbor sediment

44. The results of the study in which the cap thickness predicted in the small-scale units was used in a verification test involving Indiana Harbor sediment capped with Lake Michigan sediment are shown in Table 7. The red

swamp crayfish was used both as a member of the benthic fauna and as a source of bioturbation. The freshwater clam and the yellow perch were used to monitor the water column for the presence of contaminants.

45. Indiana Harbor sediment proved to be extremely toxic, and the contaminants from the uncapped treatment rapidly killed all crayfish, many of the perch, and several of the clams in the test. Most of the die-offs of the perch and clams occurred during the first 3 days of the test while the crayfish were still alive. Once the crayfish died, the die-off rates for the fish and clams began to decline, as did the turbidity observed in the water columns of the reaction chambers.

46. The 30-cm cap was totally effective in preventing movement of detectable levels of contaminants into the water column and almost totally effective in preventing the movement of contaminants into the biota. The only exception to this was the movement of a small amount of one metal (arsenic) through the cap and into the crayfish.

47. Since this test did not use any additional cap material above the minimum level predicted for chemical sealing of ammonium-nitrogen to allow for the effects of bioturbation, it appears that the small-column tests did a reasonable job of predicting the cap thickness required for effectiveness. However, results of these tests also point out the importance of two other considerations. <u>If only two different parameters are monitored for their rates of occurrence (uptake or release), it is better to select the maximum thickness needed to ensure 100-percent sealing for the parameter having the slower rate of decrease with increasing cap thickness.</u> In addition, this test points out the need to <u>allow extra thickness above that predicted for obtaining a satisfactory chemical seal to prevent disturbance of cap integrity by bioturbation.</u>

PART IV: DISCUSSION

48. Results of this developmental study demonstrated that small-scale tests can be used to predict, with some degree of accuracy, the thickness of a given cap material required to isolate contaminated dredged material from the water column and nonburrowing aquatic organisms. In addition, the results also demonstrated the following:

- a. The importance of using more than one chemical parameter in the small-scale tests.
- b. The importance of bioturbation as a major factor influencing capping effectiveness.
- c. The influence of the texture of capping materials on capping effectiveness.
- d. Results of small-scale tests and a knowledge of burrowing aquatic organisms in the area of the capping site can be used to estimate the cap thickness required to provide a complete chemical and biological seal for contaminated dredged material.

Chemical Parameters

49. The use of more than one chemical parameter is necessary for several reasons that were made apparent by this developmental work. First, as can be seen by comparing the results from the oxygen depletion studies with the results of the ammonium-nitrogen release studies, the results of using these parameters to monitor capping efficiency were sometimes, but not always, comparable. Cap thickness predictions made using dissolved oxygen depletion rates were similar to those predictions made using ammonium-nitrogen release rates for Dutch Kills sediment capped with Buttermilk Channel sediment and for Black Rock Harbor sediment capped with either sand or silt. Dissimilar results were obtained for Black Rock Harbor sediment capped with New Haven sediment, for diluted Black Rock Harbor sediment capped with sand, and for Indiana Harbor sediment capped with Lake Michigan sediment. In like manner, the use of orthophosphate-phosphorus as a tracer was unsatisfactory for the work with Dutch Kills and Black Rock Harbor sediments, but was effective in the work with Indiana Harbor sediment.

50. The agreement of parallel results with different parameters may be viewed as an unnecessary duplication of effort resulting in higher costs for the testing agency. As brought out by the work done here, the use of at least

two parameters may be the only means of ensuring that at least one set of usable results is obtained.

51. Another reason for using more than one parameter for monitoring cap effectiveness lies with the variations of chemical and biochemical properties that are inherent in sediments. On some occasions, the contaminated sediment and the proposed capping material will be so dissimilar that a chemical property of the contaminated sediment will be easily distinguishable from that same property of the cap material. This was observed here when relatively pristine sand and silt were used to cap heavily contaminated sediment from Black Rock Harbor. However, when the cap material begins to have some of the same chemical properties as the contaminated sediment it is intended to seal, chemical differences become harder to distinguish, as was the case for the dissolved oxygen depletion rates observed after capping Black Rock Harbor sediment with New Haven sediment. In such a case, if only one parameter were measured and negative results were obtained, the testing agency would have to set up and run a second series of tests, with consequent increased costs of time and money. An additional means of obtaining information for selecting the most appropriate parameters to use is by running determinations for ammonium-nitrogen and orthophosphate-phosphorus in the pore waters of both the contaminated sediment and proposed cap material. Those constituents having high levels in the contaminated sediment, but not in the cap material, are the best materials to monitor in the test. For the present, ammonium-nitrogen and dissolved oxygen are considered as the minimum parameters to measure. More detailed procedures for selecting the best parameters to use will be provided in the final report.

Bioturbation

Large-scale reaction tests

52. The importance of bioturbation by burrowing aquatic organisms to the mobility of contaminants cannot be overstated. In addition to the outright disruption (breaching) of a thin cap that can result when organisms actively work the surface sediments, there is the problem of direct exposure of burrowing organisms to the underlying contaminated sediment.

53. The exact measurement of the nature and extent of contaminant accumulation by aquatic biota is complicated by the large amount of variability

encountered when working with organisms. For example, previous work on capping (Rubenstein, Lores, and Gregory 1983; Brannon et al. 1985, 1986; Gunnison et al. 1986) has indicated that, under rigorously controlled conditions available in the laboratory, a large amount of variation in contaminant bioaccumulation can be observed, even when using the same organisms exposed to the same treatment. It is likely that much of the variability observed represents differences in exposure conditions caused by bioturbation.

54. In addition, differences between treatments within a given capping verification test can cause widely divergent results, such as was observed in this study during the large-scale reactor tests (paragraph 46) wherein the die-off rates of both fish and clams were observed to decrease in the Indiana Harbor sediment-only treatments once the contaminants had killed all the crayfish, and sediment resuspension due to bioturbation by the crayfish had ceased. In the control and the capped Indiana Harbor treatments, bioturbational activity by crayfish at the cap surfaces had a winnowing effect. The finer silt particles in the predominantly sand and gravel cap material were suspended into the water column by the crayfish. These particles gave the water column an opaque appearance for the first few days of these studies. However, because the large reaction chambers were equipped with flow-through water supplies, the suspended sediments were gradually swept out of the chambers. Within the first 2 weeks, the cap surfaces became composed predominantly of large sand grains and gravel, and the water columns became transparent as the silt particles were flushed out of the system.

Small column tests

55. The small-scale predictive test is used to determine the cap thickness required to obtain a chemical seal of the contaminated sediment from the overlying water column. However, the influence of bioturbation on cap effectiveness is not addressed by the small column predictive test. In addition, the procedure for assessing the cap thickness necessary to ensure cap integrity in the presence of bioturbation has not been developed. It is the investigator's opinion that the latter consideration can be addressed through the process described in the following paragraph.

56. The thickness needed to prevent breaching of cap integrity through bioturbation can be obtained indirectly from other sources. For example, the benthic biota of US coastal and freshwater areas has been fairly well examined, and the depth to which benthic animals burrow should be available from

regional authorities on these organisms. Often, the Districts may already have the necessary expertise available in-house.

Texture of Capping Material

57. The developmental work reported here demonstrated that both texture and thickness of capping material influence capping efficiency: New Haven sediment (which was largely laden with silt and clay) was more effective than silt alone, which was more effective than sand. This order of effectiveness was apparent in the required cap thicknesses of each of these materials as predicted by the small-column tests and was verified by the results of the large reaction chamber tests.

58. It is important to note that laboratory studies cannot include a large number of the environmental factors encountered in the field. For example, sand, which was the least effective material examined in these tests, is the heaviest cap material and would be the most difficult to transport by the hydrodynamic forces present in the field. A field office would have to make a decision on the trade-off between the extra cost required to attain an effective cap using a sandy material and the frequency with which repairs might have to be made if a cap containing finer, easily eroded material were used.

Estimating Required Cap Thickness

59. The effective cap thickness to obtain a chemical seal between the contaminated sediment and the overlying water column is that thickness of cap material that prevents the transfer to the water column of a minimum of two of the parameters measured. This is based on the use of at least ammonium-nitrogen and dissolved oxygen as tracers. In most cases, organic contaminants are much less mobile than ammonium or dissolved oxygen. Thus, a cap thickness that is effective for these inorganic constituents will also be effective for organic contaminants that are strongly bound to sediment; these include polynuclear aromatic hydrocarbons (PAH's), petroleum hydrocarbons, and polychlorinated biphenyls (PCB's). Other organic hydrocarbons may be mobile in water, but several are also reactive with organic matter in sediment; as a result, these often tend to become bound to the sediment. The final report for this study will discuss relative mobility of organic contaminants in more detail

and consider those inorganic contaminants that become mobile under anaerobic conditions.

60. For the present, a satisfactory answer to the question of the cap thickness T_R required to provide a complete chemical and biological seal may best be provided by the equation:

$$T_R = T_P + D_B \tag{1}$$

where

T_P = predicted thickness (cm) to obtain a chemical seal (the thickness found in the small-column tests to effectively prevent contaminant migration from contaminated sediment into the water column for at least two of the three parameters tested, i.e., dissolved oxygen depletion, ammonium-nitrogen release, and orthophosphate-phosphorus release)

D_B = depth (cm) to which the deepest burrowing organism in the region burrows (depth that most authorities on bioturbation in the region agree is the maximum for aquatic biota to normally burrow)

This simplistic approach suggests that to ensure complete cap integrity from both chemical and biological viewpoints, sufficient cap thickness must be added above the level required to obtain the chemical seal to ensure that the benthic biota will not have access to the thickness necessary for a chemical seal of the contaminated sediment.

PART V: SUMMARY AND CONCLUSIONS

61. Analysis of dissolved oxygen depletion rates and the release rates of ammonium-nitrogen, orthophosphate-phosphorus, and manganese with the use of small column predictive tests showed that dissolved oxygen depletion and ammonium-nitrogen release were generally the best tracers to use for predictive purposes. On occasion, orthphosphate-phosphorus release was also an effective tracer, but manganese releases were unsatisfactory for this purpose. Amendment of sediment with a conservative tracer, such as potassium chloride, proved ineffective.

62. The small column predictive tests revealed that increasing cap thicknesses caused a decreasing transfer of dissolved constituents into the overlying water column. The small column predictive tests also revealed differences in the efficiency of various potential capping materials. When large-scale verification tests were conducted with cap thicknesses that were lower than the thicknesses predicted by the small-scale tests, it was found that the lesser thicknesses were generally ineffective. Tests conducted with cap thicknesses greater than the predicted thicknesses were effective in preventing transfer of contaminants into the overlying water column and the biota in the water column; however, organisms burrowing through the cap and into the underlying contaminated sediment were still subject to contaminant accumulation. One verification test was conducted with the cap thickness predicted by one of three parameters in the small-scale test. Overall, the predicted thickness used in this verification test proved to be satisfactory from both a chemical and biological viewpoint, but it was apparent that additional cap material was needed for the most effective seal against biological activity.

63. The small-scale predictive tests appear to be an effective tool for determining the cap thickness required to chemically seal a contaminated sediment from the overlying water column or the biota in the water column or remaining on the sediment surface. However, it is important that the cap thickness selected from results of the small-scale tests be shown to seal a minimum of two of the three parameters used, i.e., dissolved oxygen depletion, ammonium-nitrogen release, and orthophosphate-phosphorus. To prevent exposure of benthic organisms that burrow into the sediment to contaminated sediment, it is recommended that a safety margin be added to the thickness required to achieve a chemical seal. This safety margin is determined by the depth

reached by the deepest burrowing benthic organism within the region. The sum of the thickness required to achieve the safety margin and the thickness required for the chemical seal is the depth necessary to isolate the contaminated sediment chemically and biologically from the overlying water column and all aquatic biota. This thickness does not take into account any additional material that may need to be added to allow for erosion or any other physical factors present in the environment.

64. The results from the attempts to cap sediments having densities (percent solids) below 40 percent (paragraph 30) are presently interpreted to mean that clamshell dredging, rather than hydraulic dredging, gives the better substrate of contaminated dredged material for a capping operation. However, this recommendation does not necessarily mean that all clamshell-dredged contaminated sediments are suitable for capping. On occasion, some modifications may be required to increase the density of the contaminated dredged material, decrease the density of the cap material, or otherwise prevent the capping material from sinking into the underlying contaminated dredged sediment.

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Table 1

List of Contaminated Dredged and Capping Materials

Examined in this Study

Material	Source of Material	Major Contaminants
Contaminated sediment		
Black Rock sediment	Black Rock Harbor Bridgeport, Conn.	Petroleum hydrocarbons, metals
Dutch Kills sediment	Dutch Kills Channel New York, N. Y.	Petroleum hydrocarbons, metals, PCBs*
Indiana Harbor sediment	Indiana Harbor Gary, Ind.	Petroleum hydrocarbons, metals, PCBs, pesticides
Capping material		
Sand	Vicksburg, Miss.	None
Silt loam	Vicksburg, Miss.	None
New Haven sediment	New Haven, Conn.	Petroleum hydrocarbons
Lake Michigan sediment	Lake Michigan off Gary, Ind.	Petroleum hydrocarbons, metals, PCBs, pesticides
Buttermilk Channel sediment	Buttermilk Channel, New York, N. Y.	Petroleum hydrocarbons, metals, PCBs
Edgewater Channel sediment	Hudson River New York, N. Y.	Petroleum hydrocarbons, metals, PCBs

* PCBs = polychlorinated biphenyls.

Table 2

Contaminated Sediments and Depths of Capping Materials Used for Small-Scale Predictive Tests

Contaminated Sediment	Cap Material	Cap Thickness Tested, cm	Nature of Overlying Water Column
Dutch Kills	Buttermilk Channel	0, 2, 10, 16, 22	Artificial seawater, salinity = 20 ppt
Black Rock	Sand	0, 2, 10, 14, 18, 26	Artificial seawater, salinity = 15 ppt
	New Haven	0, 2, 10, 18, 26	Artificial seawater, salinity = 15 ppt
	Vicksburg silt	0, 2, 10, 18, 26	Artificial seawater, salinity = 15 ppt
Diluted Black Rock	Sand	0, 8, 14, 26, 30	Artificial seawater, salinity = 15 ppt
Indiana Harbor	Lake Michigan	0, 5, 15, 26, 30	Aged tap water

Table 3

Water Column Oxygen Demand as a Function of Cap Thickness and Cap Material

Substrate	Oxygen Demand, $mg/m^2/day$, for Indicated Cap Thickness, cm										
	0	2	5	10	12	14	16	18	22	25	30
Dutch Kills with Buttermilk cap	1,175 (15)**	625 (10)	ND*	500 (50)	ND	ND	375 (5)	ND	350 (5)	ND	ND
Buttermilk cap alone = 345 (18)											
Black Rock Harbor with sand cap	904 (18)	585 (24)	ND	410 (23)	359 (6)	222 (27)	ND	259 (8)	116 (7)	ND	ND
Sand cap alone = 115 (1.2)											
Black Rock Harbor with New Haven cap	904 (18)	408 (8)	ND	423 (10)	ND	ND	ND	416 (6)	ND	ND	ND
New Haven cap alone = 417 (10)											
Black Rock Harbor with silt cap	904 (18)	372 (18)	ND	300 (6)	ND	ND	ND	248 (2)	ND	ND	ND
Silt cap alone = 246 (24)											
Diluted Black Rock Harbor with sand cap	261 (2)	ND	ND	ND	ND	250 (6)	ND	ND	ND	165 (3)	171 (1)
Sand cap alone = 115 (1)											
Indiana Harbor with Lake Michigan cap	410 (90)	ND	400 (100)	395 (35)	ND	ND	365 (30)	ND	ND	365 (15)	365 (15)
Lake Michigan cap alone = 145 (7)											

* Entry ND represents oxygen demand not determined for indicated depth.
** Standard error of the mean.

Table 4

Release Rate of Ammonium-Nitrogen as a Function of Cap Thickness and Cap Material

Substrate	Ammonium-Nitrogen Release Rate, $mg/m^2/day$, for Indicated Cap Thickness, cm										
	0	2	5	10	12	14	16	18	22	25	30
Dutch Kills with Buttermilk cap	151 (3)**	115 (5)	ND*	70 (6)	ND	ND	60 (2)	ND	30 (10)	ND	ND
Buttermilk cap alone = 30 (2)											
Black Rock Harbor with sand cap	312 (22)	182 (12)	ND	51 (5)	27 (6)	22 (2)	ND	25 (5)	9 (3)	ND	ND
Sand cap alone = 0											
Black Rock Harbor with New Haven cap	312 (22)	259 (1)	ND	246 (16)	ND	ND	ND	257 (17)	ND	ND	ND
New Haven cap alone = 223 (2)											
Black Rock Harbor with silt cap	312 (22)	128 (8)	ND	76 (5)	ND	ND	ND	18 (10)	ND	ND	ND
Silt cap alone = 12 (2)											
Diluted Black Rock Harbor with sand cap	222 (32)	163 (15)	ND	ND	ND	ND	158 (9)	ND	153 (8)	ND	82 (12)
Sand cap alone = 0											
Indiana Harbor with Lake Michigan cap	275 (20)	ND	185 (45)	145 (30)	ND	ND	105 (40)	ND	ND	ND	0 (30)
Lake Michigan cap alone = 0											

* Entry ND represents release rate not determined for indicated thickness.
** Standard error of the mean.

Table 5

Contaminant Uptake from Dutch Kills Sediment Capped with Buttermilk Channel Sediment

Contaminated Sediment	Cap Material	Predicted Cap Thickness cm	Tested Cap Thickness cm	Animals Used*	Contaminant Uptake
Dutch Kills	None	--	0	Clam	Accumulated PCBs
				Sandworm	Accumulated PAHs**
	Buttermilk Channel	22	10	Clam	Accumulated PCBs
				Sandworm	Accumulated PAHs
			50	Clam	No accumulation
				Sandworm	No accumulation
None	Buttermilk Channel	--	--	Clam	No accumulation
				Sandworm	No accumulation

* Clams *Mercenaria mercenaria* and sandworms *Nereis virens*.

** PAHs = polyaromatic hydrocarbons.

Table 6

Contaminant Uptake from Black Rock Harbor Sediment Capped with Three Different Materials

Contaminated Sediment	Cap Material	Predicted Cap Thickness cm	Tested Cap Thickness cm	Animals Used*	Contaminant Uptake
Black Rock Harbor	None	--	--	Clams	Accumulated PAHs and PCBs
				Sandworms	Accumulated PAHs and PCBs
	Sand	22	5	Clams	Accumulated PAHs and PCBs
				Sandworms	Accumulated PAHs and PCBs
			50	Clams	No accumulation
				Sandworms	Accumulated some PAHs and PCBs
	Silt	18	5	Clams	Assumulated PAHs and PCBs, but to a lesser extent than with the sand cap
				Sandworms	Assumulated PAHs and PCBs
			50	Clams	No accumulation
				Sandworms	Accumulated some PAHs and PCBs
	New Haven sediment	10	5	Clams	Accumulated PAHs and PCBs, but to a lesser extent than with the sand cap
				Sandworms	Accumulated PAHs and PCBs
			50	Clams	No accumulation
				Sandworms	Accumulated some PAHs and PCBs
None	Sand	--	--	Clams	No accumulation
				Sandworms	No accumulation
	Silt	--	--	Clams	No accumulation
				Sandworms	No accumulation
	New Haven sediment	--	--	Clams	No accumulation
				Sandworms	No accumulation

* Clams *Rangia* and sandworms *Nereis virens*.

Table 7

Contaminant Uptake from Indiana Harbor Sediment Capped with Lake Michigan Sediment

Contaminated Sediment	Cap Material	Predicted Cap Thickness cm	Tested Cap Thickness cm	Animals Used*	Contaminant Uptake/Effects
Indiana Harbor	None	--	0	Crayfish	All test animals died
				Perch	Most test animals died
				Clam	Accumulated PAHs and PCBs
Indiana Harbor	Lake Michigan	30	30	Crayfish	Minimal accumulation of metals, PAHs, and PCBs
				Perch	Minimal accumulation of PAHs and PCBs
				Clam	Minimal accumulation of PAHs and PCBs
None	Lake Michigan	--	--	Crayfish	Minimal accumulation of PAHs and PCBs
				Perch	Minimal accumulation of PAHs and PCBs
				Clam	Minimal accumulation of PAHs and PCBs

* Crayfish *Procambarus clarkii*, perch *Perca flavescens*, and clams *Anondontia*.